Determination of the HWW and HZZ Couplings at the LHC ^a

EDMOND L. BERGER

High Energy Physics Division, Argonne National Laboratory Argonne, Illinois 60439, USA E-mail: berger@anl.gov

ABSTRACT

The weak boson fusion process for neutral Higgs boson production is investigated with particular attention to the accuracy with which the Higgs boson couplings to weak bosons can be determined in final states that contain a Higgs boson plus at least two jets at CERN Large Hadron Collider energies. We determine that an accuracy of $\delta g/g \sim 10\%$ on the effective coupling g may be possible after the accumulation of $\sim 200~{\rm fb}^{-1}$ of integrated luminosity.

1. Introduction and Motivation

Following the discovery of the neutral Higgs boson H at the Fermilab Tevatron or the CERN Large Hadron Collider (LHC), attention will focus on the measurement of its couplings to gauge bosons and fermions. A promising reaction from which to extract some of these couplings, particularly the HWW coupling, is the weak-boson fusion (WBF) process, in which the Higgs boson is produced via fusion of the weak bosons W and Z: $WW, ZZ \rightarrow H$, and is accompanied in the final state by two jets that carry large transverse momentum p_T . In this paper, I summarize a recent study done in collaboration with John Campbell in which we simulate H+2 jet events and investigate how well the Higgs boson couplings g to the weak vector bosons, W and Z, can be determined [1].

We assume that a standard-model-like Higgs boson has been discovered with mass in the range 115 $< m_H < 200$ GeV, and that a sample exists of H+2 jet events at the LHC. We focus on two production subprocesses that contribute to the H+2 jet event sample: (1) the WBF signal subprocess $W+W\to H+X$ and $Z+Z\to H+X$, and (2) the irreducible QCD background subprocess, e.g., $g+g\to H+X$. Once a sample exists of H+2 jet events, the salient issue for the determination of couplings is this: How well can we resolve WBF production of H from QCD production of H?

In our work, we perform an independent calculation of the signal and background H+2 jet processes to gauge the effectiveness of cuts used to select the WBF signal and to evaluate the accuracy with which the coupling g can be determined. We define signal "purity" as P=S/(S+B) where S is the number of signal H+2 jet events and B is the number of H+2 jet QCD background events, both in the WBF region of phase space. We study P of the signal vs the cut on the jet transverse momentum $p_T^{\rm cut}$ used to define the event sample. We evaluate the uncertainty $\delta g/g$ of the coupling in terms of

^aArgonne report ANL-HEP-CP-04-79. To be published in the Proceedings of the 12th International Conference on Supersymmetry and Unification of Fundamental Interactions (SUSY 2004) June 17-23, 2004, Tsukuba, Japan

P, the experimental statistical uncertainty of the event sample $\delta N/N$, and the estimated theoretical uncertainties of the signal $\delta S/S$ and of the background $\delta B/B$.

2. Signal and Background; Calculations and Uncertainty Estimates

The WBF H+2 jet signal region is characterized by jets that carry large transverse momentum. Correspondingly, hard QCD matrix elements must be used in order to represent the signal and the H+2 jet background reliably. We use the dipole subtraction method to compute the NLO corrections to the WBF H+2 jet cross section in a fully differential fashion in order to examine in detail the effects of the WBF selection cuts. Our independent calculation verifies the NLO results of Ref. [2]. The NLO K-factor is modest $\sim 10\%$, and it varies but slightly over the phase space appropriate for the WBF signal. The hard perturbative scale μ dependence of the signal cross section is also modest, showing a $\pm 2\%$ change over the range $\frac{1}{2}m_H < \mu < 2m_H$. An additional $\pm 3\%$ uncertainty may be attributed to parton density variation, based on the CTEQ6 procedure for estimating such uncertainties. The WBF H+2 jet signal process can therefore be assigned a relatively small theoretical uncertainty. We use $\delta S/S \simeq 5\%$.

We also use fully differential perturbative QCD expressions for the background H+2 jet matrix elements. At present, these background distributions are known only at leading order [3]. The LO μ dependence is substantial [1] in the WBF region of phase space. The cross section is $\sim 70\%$ greater at $\mu = \frac{1}{2}m_H$ and $\sim 40\%$ less at $\mu = 2m_H$ than at $\mu = m_H$. The NLO K-factor may be estimated from NLO calculations of the inclusive rate [4], $K \sim 1.7-1.8$, and the NLO H+1 jet cross section [5], $K \sim 1.3-1.5$. At NLO, the μ dependence is less, $\sim 20\%$, and the PDF uncertainty is another 5%. For the uncertainty $\delta B/B$, we adopt the NLO estimates of μ dependence and PDF uncertainty, despite the fact that the NLO H+2 jet calculation is not complete. We use $\delta B/B \simeq 30\%$ in our subsequent estimation of $\delta g/g$.

3. Event Characteristics

The hallmark of WBF events in hadron reactions is a Higgs boson accompanied by two "tagging" jets having large $p_T \sim \mathcal{O}(\frac{1}{2}M_W)$. The QCD $gg \to H+2$ jets background process generates a softer p_T spectrum. The rapidity spectra for the WBF and QCD production mechanisms also differ, related to the fact that the gluon parton density (that plays a dominant role in generating the background) is softer than the quark density that drives the WBF signal. Motivated by our comparison of rapidity spectra [1], we choose a uniform rapidity cut to define our WBF H+2 jet sample, a cut that ensures at least one jet lies within the peak of the rapidity distribution of the WBF signal:

$$\eta_{\text{peak}} - \eta_{\text{width}}/2 < |\eta_j| < \eta_{\text{peak}} + \eta_{\text{width}}/2,$$
(1)

for $j = j_1$ or $j = j_2$, where $\eta_{\text{peak}} = 3$ and $\eta_{\text{width}} = 2.8$. This simple definition of the WBF sample offers advantages in a high luminosity environment where a large value of p_T^{cut} is appropriate and multiple events per crossing may be an issue.

Having defined our signal region, we compute event rates for the H+2 jet WBF signal and QCD background processes, and we compute the signal purity P=S/(S+B). A p_T cut of 20 GeV is barely sufficient to distinguish the WBF signal above the QCD LO background for $m_H=115$ GeV. The signal S to background S ratio improves to about 2 for $p_T^{\text{cut}} \geq 40$ GeV. At $m_H=200$ GeV, a S/B of about 1.7 is obtained for $p_T^{\text{cut}} \sim 20$ GeV, rising to ~ 3 for $p_T^{\text{cut}} \geq 40$ GeV. We determine that a p_T cut of 40 GeV yields a good S/B across the Higgs boson mass range $m_H=115-200$ GeV. Signal purities of $\sim 65\%$ are obtained for $p_T^{\text{cut}} \geq 40$ GeV; purity is greater at the larger values of m_H .

4. Coupling Uncertainties

Both the signal S and the background B have H+2 jets. The total number of events is N=S+B. We derive an equation for the uncertainty in the effective HWW coupling g in terms of purity P:

$$\delta g/g = 1/2\sqrt{[(\delta S/S)^2 + (1/P)^2(\delta N/N)^2 + ((1-P)/P)^2(\delta B/B)^2]}.$$
 (2)

A minimum of $\sim 10~{\rm fb^{-1}}$ in integrated luminosity is needed to discover the Higgs boson in the WBF process [6], corresponding to one year of LHC operation at $10^{33}~{\rm cm^{-2}s^{-1}}$. The values of N and $\delta N/N$ depend on the specific decay modes of the Higgs boson. For $m_H = 115~{\rm GeV}$, we pick $H \to \tau^+ \tau^-$, with one τ decaying to hadrons and one to leptons. For $m_H = 200~{\rm GeV}$, we use $H \to W^+W^-$, with both W's decaying to leptons. With $p_T^{\rm cut} = 40~{\rm GeV}$, we find $\delta N/N \sim 10\%$ at $m_H = 115~{\rm GeV}$ in the $H \to \tau^+ \tau^-$ mode and $\delta N/N \sim 6\%$ at $m_H = 200~{\rm GeV}$ in the W^+W^- decay mode.

After 5 years of LHC operation, we may anticipate an integrated luminosity of 200 fb⁻¹. The corresponding values are $\delta N/N \sim 2\%$ in the $\tau\tau$ mode at $m_H = 115$ GeV, and $\delta N/N \sim 1.5\%$ at $m_H = 200$ GeV in the WW mode, both for $p_T^{\rm cut} = 40$ GeV.

In Fig. 1, we show our calculation of the expected uncertainty $\delta g/g$ as a function of purity P for both high and low luminosity samples at the LHC. If $\delta N/N \sim 10\%$, we find $\delta g/g \sim 10\%$ for P=0.7. With $\delta N/N \sim 2\%$, $\delta g/g \sim 7\%$ for P=0.7. The uncertainties in S and in B dominate uncertainty in g. With P=0.7 and $\delta N/N=2\%$, $\delta S/S$ and $\delta B/B$ would have to be reduced to 3% and 6% before statistics control the answer. We conclude that P>0.65 permits $\delta g/g \sim 10\%$ after 200 fb⁻¹, obtained for $p_T^{\rm cut}>40$ GeV at $m_H=115$ GeV and for $p_T^{\rm cut}>20$ GeV at $m_H=200$ GeV. These estimates assume a LO value for B. If we suppose $K_{\rm background}^{\rm NLO}\sim 1.6$, then we find P=0.56 at $m_H=115$ GeV for $p_T^{\rm cut}>40$ GeV, and $\delta g/g$ rises to 13%. At $m_H=200$ GeV, the new values would be P=0.52 for $p_T^{\rm cut}>20$ GeV, and $\delta g/g=15\%$.

It may be suggested that greater purities and accuracies could be achieved if one of the alternative definitions of the WBF sample is used. Using a cut on the rapidity separation between the two tagging jets favored, e.g., in Ref. [2], we find that the signal rate is diminished somewhat and that the purity is greater. However, the quantitative shift from P = 0.67 to P = 0.78 at M = 115 GeV and $p_T > 40$ GeV is an improvement of only 3% in $\delta g/g$, and this reduction is offset somewhat by the loss in statistical accuracy.

Our WBF signal purity and our uncertainties are obtained in a well controlled situation in which there is an identified Higgs boson in a sample of H + 2 jet events. In an

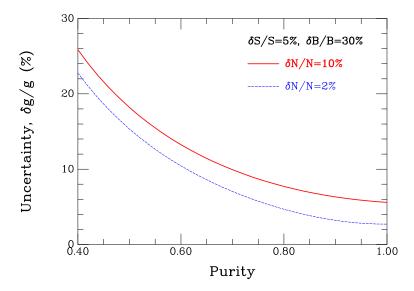


Figure 1: The predicted uncertainty $\delta g/g$ in the effective coupling of the Higgs boson to a pair of W bosons is shown as a function of signal purity P = S/(S+B) for expected statistical accuracies $\delta N/N$ of 10% and 2%, and uncertainties in knowledge of the signal S and background B of 5% and 30% respectively.

experiment, there will be additional sources of background from final states that mimic a Higgs boson, the effects of which presumably only increase the expected uncertainties.

We conclude that after 200 fb⁻¹ are accumulated at the LHC, it may be possible to achieve an accuracy $\delta g/g \sim 10\%$ in the effective coupling (combination of HWW and HZZ couplings) of the Higgs boson to weak bosons. These estimates are about a factor of 2 less optimistic than those in the Les Houches 2003 study [7]. The salient difference may be traced to assumptions in Ref. [7] about the size of the irreducible H + 2 jet QCD background. In order to reduce the estimated uncertainty in g, the next major step would be a fully differential NLO calculation of the H + 2 jet backgrounds.

5. Acknowledgments

This work was supported by the U. S. Department of Energy under contract No. W-31-109-ENG-38.

6. References

- [1] E. L. Berger and J. Campbell, arXiv:hep-ph/0403194, Phys. Rev. D. in press.
- [2] T. Figy, C. Oleari, and D. Zeppenfeld, *Phys. Rev.* **D68**, 073005 (2003).
- [3] R. P. Kauffman, S. V. Desai, and D. Risal, Phys. Rev. D55, 4005 (1997) [Erratum ibid. D58, 119901 (1998)].
- [4] R. V. Harlander and W. B. Kilgore, Phys. Rev. D64, 013015 (2001); C. Anastasiou and K. Melnikov, Nucl. Phys. B646, 220 (2002).
- [5] V. Ravindran, J. Smith, and W. L. van Neerven, Nucl. Phys. **B665**, 325 (2003).
- [6] S. Asai et al., arXiv:hep-ph/0402254.

[7] M. Duhrssen, S. Heinemeyer, H. Logan, D. Rainwater, G. Weiglein, and D. Zeppenfeld, arXiv:hep-ph/0406323.